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Project Summary

Testing the Performance of Real-Time Incinerator Emission Monitors

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In a recently completed test program at the U.S. Environmental Protection Agency (EPA) Incineration Research Facility (IRF), ten prototype or developing continuous emission monitors (CEMs) for measuring trace metal or trace organic species concentrations were tested. Of the ten CEMs tested, four measured concentrations of several specific volatile organic compounds (VOCs), one measured total particulate-bound polynuclear aromatic hydrocarbon concentrations, two measured concentrations of up to 14 trace metals, and three measured mercury concentrations. While the testing consisted of obtaining quantitative measurement data on the four measures of CEM performance checked in a relative accuracy test audit as described in 40 CFR 60 Appendix F—relative accuracy (RA), calibration drift (CD), zero drift (ZD), and response time—the primary project objective focused on the RA measurement. The RA measurement was achieved by comparing the monitored analyte concentration reported by the CEM to the concentration determined by the EPA reference method (RM) for the analyte. Four series of tests were performed, each simultaneously testing up to three monitors measuring the same or similar analyte type. Each test series consisted of performing triplicate RM measurements at each of three target flue gas monitored analyte concentrations while the tested CEMs were in operation. All measurements were taken in the wet scrubber exit flue gas from the pilot-scale rotary kiln incineration system at the IRF.

The test program results clearly showed the prototype nature of most approaches tested, and the clear need for further development. Mercury CEMs will require the least development and are nearly commercial offerings. However, the approaches tested for multimetals and VOC determinations require further development. Given this need, the importance of continuing test programs of the scope and scale of this one cannot be overemphasized.

This Project Summary was developed by EPA's National Risk Management Research Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

EPA is currently developing more stringent emission standards and considering changes in the way that permits for waste combustion facilities are handled. More public involvement in the process has been proposed. Because the public's apparent perception of incinerators is that high concentrations of hazardous compounds are continually being released from the stacks of the thermal treatment devices, a means by which the "real-time" (defined as ranging from instantaneous to within several hours) organic and metals emissions can be monitored would be of great benefit to both regulators and the regulated commu-

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nity. The ability to have "immediate" knowledge of stack emissions would provide assurances that the thermal treatment device is operating correctly or indicate the change of operating conditions needed to adjust stack emissions. Thus, having this monitoring capability would constitute one means of responding to and allaying the public's fears by showing that good, safe, and clean combustion practices can be demonstrated.

Several developers have designed monitoring units that they claim will measure various regulated hazardous compounds using a number of different innovative concepts and technologies. The development of these CEM approaches for both trace metal and trace organic analyte classes has advanced to the state that several candidate approaches are now in the prototype instrument stage. Given this, the general objective of the project reported herein was to test several prototype instruments and establish or estimate for each unit the effectiveness, reliability, accuracy, and detection limit.

For this test program, ten developing CEM approaches were tested. These are listed in Table 1 by monitored analyte class. As shown, included in the list of CEMs tested in this program are one semivolatile organic constituent (SVOC), four VOC, two multi-metal, and three mercury CEMs.

Test Program

The selected approaches evaluated in this test program were performed in the pilot-scale rotary kiln incineration system (RKS) at EPA's IRF, located in Jefferson, AR. The testing consisted of obtaining quantitative measurement data on four measures of CEM performance checked in a relative accuracy test audit of a CEM as described in 40 CFR 60 Appendix F. These measures are RA, CD, ZD, and response time.

Measuring a CEM's RA requires comparing the monitored analyte concentration reported by the CEM to the concentration determined by the RM for the analyte. In this program, the RM for trace metal (including mercury) monitors was draft Method 29, the EPA multiple metals method documented in the boiler and industrial furnace rules. The RM for VOCs was Method 0030 with analysis using thermal desorption, purge and trap by Method 5040, and quantitation by Method 8015A. The RM for SVOCs was Method 0010 with analysis by Method 8270B.

Test Facility

Figure 1 is a process schematic of the RKS as configured for these tests. The RKS consists of a primary combustion chamber, a transition section, and a fired afterburner chamber. After exiting the afterburner extension, flue gas flows through a quench section that is followed by a primary air pollution control system (APCS). The initial element of the primary APCS for these tests was the venturi scrubber/packed-column scrubber combination shown in Figure 1. This scrubber system removes from the flue gas most of the coarse particles and any acid gas, such as HCl. Following the scrubber system, the flue gas is reheated to about 120°C (250°F) by a 100-kW electric duct heater, then passed through a fabric filter (baghouse). The baghouse removes most of the remaining flue gas particles. Downstream of the baghouse, a backup, secondary APCS, comprised of an activated-carbon adsorber and a high-efficiency particulate air filter is in place. The CEMs tested in this program sampled flue gas at the scrubber exit location.

Testing Procedures

The test program consisted of four series of tests; each series tested one set of CEMs, generally monitoring the same analyte set. Up to three CEMs were tested at the same time during each of the four test series. The major portion of the test program consisted of performing three sequential RM measurements, while the tested CEMs were in operation, at each of three flue gas concentrations of monitored analytes. Thus, each test series was designed to supply nine sets of parallel RM and CEM reading data, three at each of three analyte concentrations. These nine sets of parallel RM and CEM data supported the calculation of each CEM's RA. Thus, up to three RAs were calculated for each CEM, one at each of the three flue gas concentrations tested. Other test efforts supported the measurements of CD, ZD, and response time.

Test Waste Feed

The incinerator feed material was a synthetic hazardous waste comprised of an attapulgite clay solid sorbent combined with a mixture of 14 trace metals and VOCs. The mixture of VOCs added to the sorbent base contained 76% toluene by weight, with 12% each of chlorobenzene and tetrachloroethene. This mixture was combined with the clay sorbent in the ratio of 1.0 kg of organic constituent mixture to 2.4 kg of clay. The mixture was a free-flowing solid with no freestanding liquid and was continuously fed to the RKS via a screw feeder system. For all tests, the target clay/organic mixture feedrate was 68 kg/hr (150 lb/hr). The target kiln exit gas temperature was 870°C (1,600°F), and the target afterburner exit gas temperature was 1,065°C (1,950°F).

Table 1. Participants in the CEM Test Program

Monitored Analyte	Developer	Approach
SVOCs	EcoChem	Photoionization of aerosol-bound polycyclic aromatic hydrocarbons
VOCs	EcoLogic	Continuous chemical ionization mass spectrometry
	Marine Shale Processors (MSP)	Continuous online mass spectrometry
	Oak Ridge National Laboratory (ORNL)	Direct sampling ion trap mass spectrometry
	EPA, Air Pollution Prevention and Control Division (APPCD)	Online gas chromatography with dual flame ionization, electron capture detection
Multi-metals	Sandia National Laboratories (SNL)	Laser induced plasma spectroscopy
	Metorex	Extractive beta gauge particulate monitor with x-ray fluorescence metals analysis
Mercury	Perkin-Elmer	Gold trap amalgamation collection, cold vapor atomic absorption spectroscopy analysis
	Senova	Noble metal film solid state chemical microsensor
	EcoChem	Cold vapor atomic absorption spectroscopy

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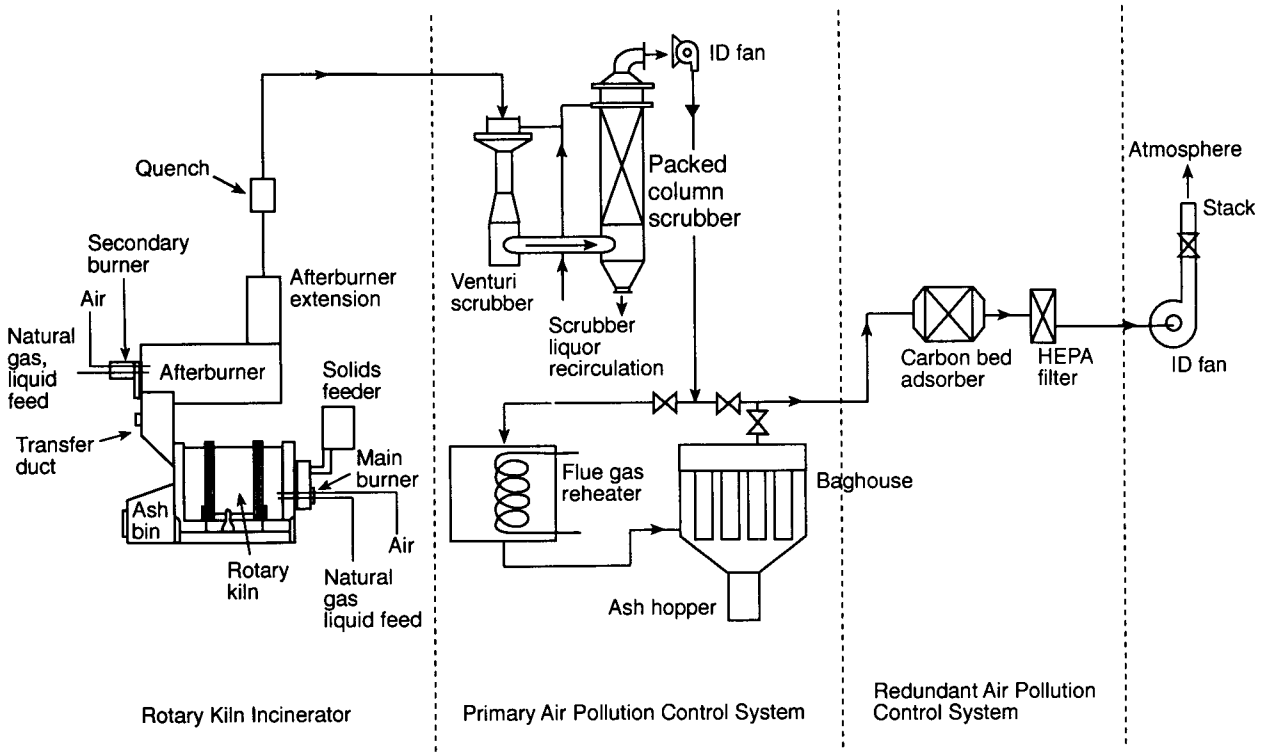

Figure 1. Schematic of the IRF rotary kiln incineration system.

Multi-Metal and Mercury CEM Tests

The trace metals of interest to the test program are listed in Table 2, which also notes the program target scrubber exit flue gas concentrations of each metal for the tests of multi-metals CEMs. For the mercury CEMs tests in Test Series 3, the low concentration targets were at half the levels noted in the low concentration column in Table 2. The intermediate concentration targets were those noted in the low concentration column in Table 2. The high concentration targets were those noted in the intermediate concentration column in Table 2. This change was incorporated at the request of the mercury CEM developers.

Trace metals were added to the RKS, to result in scrubber exit flue gas levels, via two routes. Both routes used an aqueous spike solution of the metals. A concentrated solution was added for the multi-metal CEM test days at the high target flue gas metals concentration. This concentrated solution was diluted for the multi-metal CEM test days at the intermediate and low target concentrations and for the mercury CEM tests. The two routes of metals addition were incorporated into the clay/organic mixture and atomized into the kiln main burner flame.

VOC and SVOC CEM Tests

The VOCs present in the scrubber exit flue gas for all tests included benzene, carbon tetrachloride, chlorobenzene, chloroform, 1,2-dichloroethane, 1,1-dichloroethene, tetrachloroethene, toluene, 1,1,1-trichloroethane, and trichloroethene. The target flue gas concentrations of the compounds were in the 2, 20, and 200 µg/dscm ranges (low, intermediate, and high concentrations). Naphthalene, phenanthrene, and pyrene were the SVOCs introduced into the flue gas for all tests, at the same target flue gas concentrations noted above.

The VOCs and SVOCs were introduced into the flue gas by metering a solution of the spiking compounds in methanol through a length of fine bore stainless steel tubing into the afterburner extension at its centerline. The afterburner exit flue gas was partially quenched to a temperature of between 360° to 427°C (680° and 800°F) by a water spray introduced at the

Table 2. Test Trace Metals and Target Flue Gas Concentrations

Metal	Target Flue Gas Concentration, µg/dscm		
	Low	Intermediate	High
Antimony (Sb)	10	40	400
Arsenic (As)	5	20	200
Barium (Ba)	50	200	2,000
Beryllium (Be)	0.5	2	20
Cadmium (Cd)	5	20	200
Chromium (Cr)	20	80	560
Cobalt (Co)	10	40	400
Lead (Pb)	50	200	2,000
Manganese (Mn)	5	20	200
Mercury (Hg)	20	80	800
Nickel (Ni)	10	40	400
Selenium (Se)	40	200	2,000
Silver (Ag)	5	20	200
Thallium (Tl)	5	20	200

beginning of the afterburner extension. A concentrated organic spiking solution was prepared and used for the high target flue gas VOC and SVOC CEM tests. The concentrated solution was diluted appropriately for the intermediate and low target flue gas concentration tests.

Test Results

VOC CEM Tests

Tables 3 through 5 present the results of the three sequential RM measurements, along with the Oak Ridge National Laboratory (ORNL) and EcoLogic CEM results, for each of the three VOC concentrations tested in Test Series 1. The EcoLogic CEM data for the first day of testing at the low VOC concentration were not reported in EcoLogic's test report because of operator error that resulted in CEM readings that were inflated and incorrect. RAs calculated using the RM and CEM data in Tables 3 through 5 are summarized in Table 6. The data in Table 6 show that the calculated RAs for the ORNL CEM ranged from 123% to 305% at the low test concentration, with an average of 196% over the seven compounds reported. ORNL CEM RAs were improved at the intermediate test concentration, at 113% to 278%, with an average of 154% over the nine compounds reported. Further improvement is seen at the high test concentration, with an RA range of 84% to 144%, and an average of 105% over all ten compounds reported. In fact, the RA for all VOCs reported uniformly improved as the test concentration increased.

Table 3. Measured Flue Gas Concentrations for the Test of the ORNL and EcoLogic CEMs at the Low VOC Concentration

	Concentration, µg/dscm								
	1st Daily RM			2nd Daily RM			3rd Daily RM		
Compound	RM	ORNL	Eco-Logic	RM	ORNL	Eco-Logic	RM	ORNL	Eco-Logic
Benzene	32.4	1.3	NO[a]	41.9	1.6	NO	59.6	1.6	NO
Carbon tetrachloride	31.2	<0.4	NO	34.2	<0.4	NO	38.0	0.92	NO
Chlorobenzene	55.6	0.76	NO	49.2	1.2	NO	86.7	5.6	NO
Chloroform	40.8	0.56	NO	47.3	0.4	NO	41.6	3.6	NO
1,2-Dichloroethane	2.4	2.5	NO	3.3	1.5	NO	2.6	6.8	NO
1,1-Dichloroethene	86.4	3.2	NO	35.6	<0.4	NO	16.9	11.0	NO
Tetrachloroethene	89.9	1.7	NO	73.9	1.3	NO	126	4.3	NO
Toluene	352	9.2	NO	316	9.2	NO	462	16	NO
1,1,1-Trichloroethane	2.5	<0.4	NO	4.6	<0.4	NO	6.4	<0.4	NO
Trichloroethene	6.9	<0.4	NO	5.9	<0.4	NO	3.9	<0.4	NO

[a]NO=CEM not operational.

Table 4. Measured Flue Gas Concentrations for the Test of the ORNL and EcoLogic CEMs at the Intermediate VOC Concentration

	Concentration, µg/dscm								
	1st Daily RM			2nd Daily RM			3rd Daily RM		
Compound	RM	ORNL	Eco-Logic	RM	ORNL	Eco-Logic	RM	ORNL	Eco-Logic
Benzene	32.7	12.0	97	28.7	<2.3	820	36.4	5.5	870
Carbon tetrachloride	46.9	10.1	7.9	41.7	3.8	24	58.5	6.4	16
Chlorobenzene	59.8	25.8	81	46.3	7.2	81	74.3	27.6	98
Chloroform	57.1	23.9	140	56.7	9.6	230	66.3	18.4	170
1,2-Dichloroethane	17.4	43.3	210	12.3	16.6	340	15.3	29.5	290
1,1-Dichloroethene	24.0	55.3	320	20.5	26.7	430	14.3	40.5	370
Tetrachloroethene	81.4	11.1	120	64.1	2.5	770	101	7.4	710
Toluene	342	147	210	218	71.8	120	413	103	250
1,1,1-Trichloroethane	13.8	<2.3	800	13.3	<2.3	910	12.9	<2.3	840
Trichloroethene	19.4	4.6	420	18.6	0.9	770	20.4	1.8	510

Table 5. Measured Flue Gas Concentrations for the Test of the ORNL and EcoLogic CEMs at the High VOC Concentration

	Concentration, μg/dscm								
	1st Daily RM			2nd Daily RM			3rd Daily RM		
Compound	RM	ORNL	Eco-Logic	RM	ORNL	Eco-Logic	RM	ORNL	Eco-Logic
Benzene	102	36.8	140	89.1	50.7	160	91.3	28.6	190
Carbon tetrachloride	423	101	380	409	119	350	446	76.4	360
Chlorobenzene	337	138	250	299	170	270	269	97.6	280
Chloroform	417	101	330	411	168	350	413	91.2	390
1,2-Dichloroethane	184	88.4	450	174	114	500	183	6.3	540
1,1-Dichloroethene	116	38.7	350	140	44.2	440	162	35.9	480
Tetrachloroethene	429	62.6	690	374	61.7	740	324	37.8	690
Toluene	1,760	847	1,300	1,393	921	1,200	1,024	460	760
1,1,1-Trichloroethane	175	24.9	170	164	37.8	190	182	20.3	210
Trichloroethene	189	15.7	340	176	19.3	300	185	14.7	360

Table 6. Relative Accuracies of the ORNL and EcoLogic CEMs

	RA,%					
	ORNL			EcoLogic		
	Test Concentration			Test Concentration		
Compound	Low	Intermediate	High	Low	Intermediate	High
Benzene	173	119	98	NC	5,020	154
Carbon tetrachloride	NC[a]	129	100	NC	135	27
Chlorobenzene	164	93	84	NC	74	52
Chloroform	123	105	97	NC	396	33
1,2-Dichloroethane	305	278	144	NC	2,890	239
1,1-Dichloroethene	299	277	115	NC	2,520	283
Tetrachloroethene	162	142	113	NC	1,640	128
Toluene	145	131	88	NC	65	47
1,1,1-Trichloroethane	NC	NC	110	NC	7,320	36
Trichloroethene	NC	113	103	NC	5,140	116
Average[b]	196	154	105	NC	2,520	121
Median[b]	164	129	100, 103	NC	1,640, 2,520	52, 116

[a] NC=Not calculated.
[b] Average and median excludes NC entries.

For the intermediate test concentration, the RAs of the EcoLogic CEM ranged from 65% to 7,320%, with an average of 2,520%. Improved performance was seen at the high test concentration, for which the RA ranged from 27% to 283% and averaged 121%. As seen for the ORNL CEM, the RAs for nine of the ten VOCs reported were improved at the high test concentration compared to the intermediate concentration.

Tables 7 through 9 present the results of the three sequential RM measurements, along with the EPA/APPCD and MSP CEM results, for each of the three VOC concentrations tested in Test Series 4. The tables indicate that, out of the nine sampling periods, MSP obtained data for only two periods. RAs corresponding to the RM/CEM concentration data given in Tables 7 through 9 are summarized in Table 10. The data in Table 10 show that the RAs for the EPA CEM ranged from 71% to 3,190% and averaged 638% for the low test concentrations. The relatively high average RA was driven by the two very high RAs for 1,2-dichloroethane and 1,1-dichloroethene. These two compounds were found in EPA/APPCD system blanks. EPA/APPCD's decision not to blank-correct their data led to the corresponding high RAs. The median RA for the low concentration test at a much improved 113%

Table 7. Measured Flue Gas Concentrations for the Test of the EPA/APPCD and MSP CEMs at the Low VOC Concentration

	Concentration, µg/dscm								
	1st Daily RM			2nd Daily RM			3rd Daily RM		
Compound	RM	EPA/ APPCD	MSP	RM	EPA/ APPCD	MSP	RM	EPA/ APPCD	MSP
Benzene	8.2	21.31	NO[a]	5.9	29.93	795	8.4	22.21	707
Carbon tetrachloride	13.9	9.68	NO	11.9	5.99	118	13.3	4.99	126
Chlorobenzene	21.6	18.56	NO	20.8	29.16	143	16.0	18.8	60.2
Chloroform	15.8	16.95	NO	18.4	14.89	3,439	15.8	9.25	1,515
1,2-Dichloroethane	1.8	43.21	NO	1.5	39.18	73.7	1.6	30.33	78.5
1,1-Dichloroethene	2.0	76.34	NO	6.3	90.23	322	5.1	84.49	271
Tetrachloroethene	32.7	15.65	NO	26.9	31.7	124	20.6	8.56	107
Toluene	160.9	131.92	NO	149.4	221.38	1,308	97.1	57.85	814
1,1,1-Trichloroethane	2.1	2.21	NO	1.9	2.22	3.6	1.8	3.53	4.1
Trichloroethene	2.6	2.18	NO	2.9	2.71	3,022	3.0	1.74	1,602

[a]NO=Not operational.

Table 8. Measured Flue Gas Concentrations for the Test of the EPA/APPCD and MSP CEMs at the Intermediate VOC Concentration

	Concentration, µg/dscm								
	1st Daily RM			2nd Daily RM			3rd Daily RM		
Compound	RM	EPA/ APPCD	MSP	RM	EPA/ APPCD	MSP	RM	EPA/ APPCD	MSP
Benzene	33.9	35.8	NO[a]	32.9	42.41	NO	33.6	50.34	NO
Carbon tetrachloride	53.5	31.45	NO	57.8	37.58	NO	64.1	40.55	NO
Chlorobenzene	29.5	24.86	NO	64.6	54.15	NO	75.0	40.73	NO
Chloroform	43.2	26.33	NO	62.1	31.61	NO	63.5	43.31	NO
1,2-Dichloroethane	20.7	27.97	NO	18.1	34.9	NO	16.6	55.71	NO
1,1-Dichloroethene	14.2	47.14	NO	11.3	54.48	NO	9.9	101.19	NO
Tetrachloroethene	39.3	22.87	NO	92.7	58.32	NO	96.8	30.3	NO
Toluene	143	90.22	NO	498.5	306.1	NO	551.8	163.48	NO
1,1,1-Trichloroethane	17.3	13.68	NO	16.2	14.33	NO	17.4	14.54	NO
Trichloroethene	22.9	16.04	NO	20.6	16.63	NO	19.1	15.74	NO

[a]NO=Not operational.

to 137%, removes the dominant influence of the two compounds for which the CEM did poorly. The RAs for the EPA CEM were improved at the intermediate test concentration, ranging from 29% to 1,130% and averaging 213%. Poor performance in quantitating 1,2-dichloroethane and 1,1-dichloroethene again accounts largely for the high average RA. Again, the median RA at 83% to 98% better reflects the mean performance of the CEM by removing the dominant influence of the RAs for the two VOCs poorly quantitated. Further improved performance of the EPA CEM was seen at the high test concentration, with an RA range from 34% to 133% and an average RA of 73%. In fact, at the high test concentration, the RAs for two compounds poorly quantitated at the low and intermediate test concentrations are more in line with those calculated for the other

Table 9. Measured Flue Gas Concentrations for the Test of the EPA/APPCD and MSP CEMs at the High VOC Concentration

	Concentration, µg/dscm								
	1st Daily RM			2nd Daily RM			3rd Daily RM		
Compound	RM	EPA/ APPCD	MSP	RM	EPA/ APPCD	MSP	RM	EPA/ APPCD	MSP
Benzene	102.6	96.33	NO[a]	129.5	98.73	NO	117.7	88.66	NO
Carbon tetrachloride	222.5	209.55	NO	266.2	205.53	NO	283.7	135.72	NO
Chlorobenzene	104.8	119.78	NO	146.5	113.78	NO	127.2	126.99	NO
Chloroform	229.4	190.9	NO	243.8	199.06	NO	241.1	178.42	NO
1,2-Dichloroethane	93.7	95.44	NO	121.2	107.96	NO	114.9	90.81	NO
1,1-Dichloroethene	65.9	113.67	NO	65.5	124.81	NO	71.9	144.06	NO
Tetrachloroethene	112.8	150.65	NO	162.6	161.66	NO	132.2	131.62	NO
Toluene	176.6	191.23	NO	445.4	213.8	NO	261.5	217.23	NO
1,1,1-Trichloroethane	97.8	92.89	NO	106.8	87.31	NO	103.5	57.93	NO
Trichloroethene	98.2	98.46	NO	114.3	91.81	NO	113.1	70.04	NO

[a]NO=Not operational.

Table 10. Relative Accuracies of the EPA/APPCD and MSP CEMs

	RA,%			
	EPA/APPCD			MSP
	Test Concentration			Test Concentration
Compound	Low	Intermediate	High	Low
Benzene	429	83	48	18,300
Carbon tetrachloride	86	45	95	1,200
Chlorobenzene	87	98	53	3,150
Chloroform	76	71	34	85,800
1,2-Dichloroethane	3,190	334	40	6,740
1,1-Dichloroethene	2,040	1,130	133	10,700
Tetrachloroethene	137	134	50	673
Toluene	113	158	138	3,040
1,1,1-Trichloroethane	150	29	73	315
Trichloroethene	71	45	70	384,000
Average	638	213	73	51,400
Median	113, 137	83, 98	53,70	3,150, 6,740

eight compounds. For this reason, the median RA at 53% to 70% is comparable to the average RA.

The calculated RAs based on the two available CEM/RM measurement pairs for the MSP CEM were quite large, ranging from 315% to 412,000% and averaging 54,600%. Even the median RAs for the MSP CEM, at 2,840% to 6,480%, are quite high.

SVOC CEM Tests

The SVOC CEM tests were performed at the same time as the second set of VOC CEM tests. Table 11 presents the results of the three sequential RM measurements performed each test day, and compares these to the EcoChem CEM results for the test days at the low and intermediate SVOC concentrations. Due to problems in the flue gas conditioning (moisture removal) system, the EcoChem CEM could not be brought into operation on the last day of testing at the high SVOC concentration. In addition, no CEM data were obtained during the first RM period on the intermediate concentration test day because the EcoChem CEM was not in operation, again due to problems with the flue gas moisture removal system.

Table 11 also notes the RA of the EcoChem PAH CEM for the two test days the CEM was in operation. The table indicates that the RAs for the

Table 11. Measured Flue Gas Concentrations for the Tests of the EcoChem PAH CEMs

Test	Concentration, µg/dscm 1st Daily RM	2nd Daily RM	3rd Daily RM	RA,%
Low Concentration Test				
Naphthalene	1.7	1.8	1.7	
Phenanthrene	1.3	1.2	1.3	
Pyrene	1.0	0.8	0.9	
Total PAH	4.0	3.8	3.9	
EcoChem CEM	6.9	14.8	15.5	527
Intermediate Concentration Test				
Naphthalene	17.5	10.9	15.8	
Phenanthrene	15.7	10.1	15.3	
Pyrene	9.1	19.6	9.7	
Total PAH	42.3	40.6	40.8	
EcoChem CEM	NO[a]	33.2	39.0	99
High Concentration Test				
Naphthalene	97.0	NP[b]	NP	
Phenanthrene	91.4	NP	NP	
Pyrene	68.2	NP	NP	
Total PAH	256.6	NP	NP	
EcoChem CEM	NO	NO	NO	NC[c]

[a]NO=Not operational.
[b]NP=Not performed.
[c]NC=Not calculated.

Table 12. Measured Flue Gas Concentrations for the Test of the SNL and Metorex CEMs at the Low Metals Concentrations

Metal	Concentration, µg/dscm 1st Daily RM RM	SNL	Metorex	2nd Daily RM RM	SNL	Metorex	3rd Daily RM RM	SNL	Metorex
Antimony (Sb)	4.5	ND[a]	ND	5.1	ND	ND	4.5	ND	5.13
Arsenic (As)	4.4	ND	3.65	3.8	ND	0.83	3.6	ND	1.19
Barium (Ba)	11.7	ND	ND	15.8	ND	ND	18.6	ND	6.23
Cadmium (Cd)	9.7	ND	2.63	12.1	ND	ND	13.2	ND	10.02
Chromium (Cr)	22.3	ND	2.49	23.5	ND	0.56	28.0	ND	22.29
Cobalt (Co)	7.8	ND	12.11	7.1	ND	ND	7.1	ND	14.68
Lead (Pb)	101	ND	11.51	85.6	ND	9.06	110	ND	12.36
Manganese (Mn)	21.8	ND	5.89	29.2	ND	ND	31.6	ND	19.43
Nickel (Ni)	39.6	ND	27.52	29.1	ND	6.15	42.4	ND	21.87
Selenium (Se)	11.4	ND	1.51	12.3	ND	1.47	12.3	ND	3.62
Thallium (Tl)	1.1	ND	ND	1.5	ND	ND	1.7	ND	ND

[a]ND=Not detected.

EcoChem CEM were 527% and 99%. As was seen in the VOC CEM tests, the RA at the higher test flue gas concentration was improved in comparison to the lower test concentration.

Multi-Metal CEM Tests

Tables 12 through 14 summarize the results of the three sequential RM measurements performed each test day and compares these to the Sandia National Laboratories (SNL) and Metorex CEM measurements. Neither CEM measured beryllium or mercury, so these metals are not included in the three tables. In addition, results for silver are not included in the tables. Spike recovery from QA samples was poor, so silver concentra-

Table 13. Measured Flue Gas Concentrations for the Test of the SNL and Metorex CEMs at the Intermediate Metals Concentrations

	Concentration, µg/dscm								
	Reference Method 1			Reference Method 2			Reference Method 3		
Metal	RM	SNL	Metorex	RM	SNL	Metorex	RM	SNL	Metorex
Antimony (Sb)	11.0	ND[a]	39.73	11.6	ND	22.00	9.5	ND	8.49
Arsenic (As)	11.1	63	11.92	10.8	42	0.74	8.7	115	6.61
Barium (Ba)	78.0	251	44.37	80.0	199	11.87	49.2	463	9.92
Cadmium (Cd)	14.0	ND	7.22	15.0	ND	26.93	14.2	ND	10.09
Chromium (Cr)	54.7	ND	56.48	59.5	ND	72.51	50.3	ND	25.68
Cobalt (Co)	32.3	ND	14.72	33.9	ND	20.79	27.4	ND	9.79
Lead (Pb)	141	144	107.07	141	93	51.80	136	106	40.86
Manganese (Mn)	24.2	ND	61.4	24.6	ND	55.58	18.2	ND	31.25
Nickel (Ni)	59.9	ND	26.48	61.2	ND	21.26	52.6	ND	15.76
Selenium (Se)	43.2	ND	29.34	54.5	ND	21.27	53.2	ND	18.12
Thallium (Tl)	11.1	ND	12.96	11.2	ND	4.49	12.4	ND	2.72

[a]ND=Not detected.

Table 14. Measured Flue Gas Concentrations for the Test of the SNL and Metorex CEMs at the High Metals Concentrations

	Concentration, µg/dscm								
	Reference Method 1			Reference Method 2			Reference Method 3		
Metal	RM	SNL	Metorex	RM	SNL	Metorex	RM	SNL	Metorex
Antimony (Sb)	114	233	27.32	75.7	186	18.35	43.5	131	6.59
Arsenic (As)	82.2	75	21.82	64.8	86	13.28	54.8	65	4.68
Barium (Ba)	331	650	207.37	484.3	ND[a]	111.07	285	ND	27.29
Cadmium (Cd)	88.0	ND	33.58	60.9	ND	31.73	88.7	ND	22.18
Chromium (Cr)	425	ND	129.33	299	ND	91.85	241	ND	34.70
Cobalt (Co)	357	ND	100.16	229	ND	67.47	248	ND	37.62
Lead (Pb)	1,650	ND	297.20	1,082	ND	282.71	2,176	54	167.04
Manganese (Mn)	179	ND	52.89	89.9	ND	35.25	95.6	ND	16.56
Nickel (Ni)	550	ND	160.10	347	ND	111.42	429	ND	67.89
Selenium (Se)	421	ND	102.52	399	ND	96.70	383	ND	39.92
Thallium (Tl)	114	ND	32.29	94.3	ND	28.10	113	ND	16.84

[a]ND=Not detected.

tions as measured by the RM are highly suspect. The SNL CEM did not detect any of the test trace metals on the low concentration test day, only arsenic, barium, and lead were reported on the intermediate concentration test day, and only antimony, arsenic, barium, and lead for one or more RM periods were reported on the high concentration test day.

The RAs corresponding to the measurement pair data in Tables 12 through 14 are summarized in Table 15. The data in Table 15 show that the RAs for the SNL CEM ranged from 64% to 1,560% for the three metals reported on the intermediate concentration test day, and from 65% to 188% for the two metals reported on the high concentration test day. RAs for the Metorex CEM ranged from 88% to 236%, with an average of 129% and a median of 116% for the low concentration test. Corresponding RAs for the intermediate concentration test were 72% to 467%, with an average of 168% and a median of 135%, and, for the high concentration test, 93% to 177%, with an average of 129% and a median of 121%. The RAs for the Metorex CEM were comparable for each test concentration. No marked improvement as flue gas concentration increased, as observed for the VOC CEMs, is seen in the Metorex CEM data.

Table 15. Relative Accuracies of the SNL and Metorex CEMs

	RA,%					
	SNL			Metorex		
	Test Concentration			Test Concentration		
Metal	Low	Intermediate	High	Low	Intermediate	High
Antimony (Sb)	NC[a]	NC	188	NC	467	158
Arsenic (As)	NC	1,560	65	125	174	101
Barium (Ba)	NC	905	NC	NC	135	153
Cadmium (Cd)	NC	NC	NC	89	177	123
Chromium (Cr)	NC	NC	NC	158	94	113
Cobalt (Co)	NC	NC	NC	236	72	118
Lead (Pb)	NC	64	NC	115	112	177
Manganese (Mn)	NC	NC	NC	116	261	146
Nickel (Ni)	NC	NC	NC	88	77	121
Selenium (Se)	NC	NC	NC	104	113	93
Thallium (Tl)	NC	NC	NC	NC	171	111
Average[b]	—	843	127	129	168	129
Median[b]	—	905	65, 188	116	135	121

[a]NC=Not calculated.
[b]Average and median exclude RAs NC.

Mercury CEM Tests

Table 16 summarizes the results of three sequential RM measurements performed each mercury CEM test day and compares these to the corresponding three mercury CEM measurements. Calculated RAs for each CEM are also given in the table for the three test days, each representing a different flue gas mercury concentration. The table indicates several periods during which the Perkin-Elmer and the Senova CEMs were not in operation.

The data in Table 16 show that the EcoChem CEM had an RA of about 60% for both the low and the high concentration tests. The RA at the intermediate concentration was increased, at 92%. The RA of the Perkin-Elmer CEM was 602% at the low mercury concentration and 1,150% (based on two measurement pairs) at the intermediate mercury concentration. The RA of the Senova CEM was 186% at the one test concentration having data.

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Table 16. Measured Flue Gas Concentrations and RAs for the Mercury CEM Tests

	Mercury Concentration, µg/dscm			
Test	RM	EcoChem CEM	Perkin-Elmer CEM	Senova CEM
Low Mercury Concentration				
RM 1	21	22	78	NO[a]
RM 2	16	20	42	NO
RM 3	13	19	11	NO
RA,%		60	602	NC[b]
Intermediate Mercury Concentration				
RM 1	56	83	61	NO
RM 2	34	43	NO	NO
RM 3	40	56	125	NO
RA,%		92	1,150	NC
High Mercury Concentration				
RM 1	119	137	NO	232
RM 2	94	81	NO	116
RM 3	86	62	405	165
RA,%		61	NC	186

[a]NO=Not operational.
[b]NC=Not calculated.

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The complete report, entitled "Testing the Performance of Real-Time Incinerator Emission Monitors," (Order No. PB97-142871; Cost: $38.00, subject to change) will be available only from
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